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HIGHWAY BRIDGES ON DEEP FOUNDATIONS

by Louis Duclos, M. ASCE

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PAPERS

HIGHWAY BRIDGES ON DEEP FOUNDATIONS

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Synopsis

Many bridges on deep foundations have been built in Louisiana and these bridges have presented construction and design problems which have been overcome by basic engineering principles used in conjunction with sound construction methods. This paper outlines a few methods for determining the depths at which piers should be set, especially at bridge sites where rock cannot be reached. Although pier design is primarily the engineer's responsibility, it is concluded that the contractor should be allowed latitude in selecting the method of construction.

Introduction

The design and construction of deep foundations are among the most difficult operations of bridging a river. One of the most critical features of the design is the determination of the depth of the pier in locations where rock or or other hard materials cannot be reached. It is necessary to determine the amount of penetration into the ground to assure that the base of the pier will be in material which can support the loads from the pier without excessive settlement. For channel piers, two factors of importance are the depth required to make the pier safe from undermining by scouring action and the amount of scouring which might occur.

Subsurface Conditions

Borings.—Borings should be made before the final design of the pier is attempted. If the length of the spans is determined by navigation requirements, as is usually the case for bridges over large streams or rivers, the piers should be located and the borings made at the exact location of the piers. Two borings should be made at each pier site, and additional borings should be made if the original borings indicate extensive variations in the subsurface material.

If the length of the spans is not fixed by navigation requirements, and there

is some latitude in the choice of span length, sufficient preliminary borings should be made to establish a reasonably accurate soil profile. This procedure will permit making comparative layouts with the assurance that the preliminary pier designs for these layouts will not be too unlike the final pier designs. After the most economical or desirable layout is determined from the trial designs, the final borings are made at the selected pier locations.

The types of borings made are influenced by many factors. Wash borings, even for preliminary investigations, are generally considered unsatisfactory. Dry-sample borings furnish representative samples of the material, are considered satisfactory for preliminary investigations, and may furnish all the information necessary for the final design. However, in compressible cohesive soils undisturbed samples should be obtained in order that shear and consolidation laboratory tests can be made.

The depth of the borings is affected by many factors and cannot be predicted without some knowledge of the soil. In general, borings should be deep enough to assure that there are no soft compressible materials below the base of the piers which might cause undesirable settlements. To fulfil this condition, borings under the center of the pier must extend to a depth at which the additional pressure caused by the pier loads is not more than 10% greater than the average additional pressure immediately under the pier base. It is unlikely that this slight additional pressure would cause any appreciable settlement of the pier founded upon material at this depth. To determine this depth, it is necessary to make a trail design of the pier and to estimate the depth at which the additional pressure is only 10% greater than the average additional pressure immediately under the base as computed by use of the Boussinesq equation or Westergaard equation.

Scouring Action.—After the borings have been made, the depth of the pier for stability and safety from scour must be determined. A preliminary estimate of the depth at which scouring might be expected to occur can be obtained from the log of the borings and an examination of the soil samples, but this estimate is mainly a question of judgment. The best guide as to the amount of scouring which can be expected is the examination of the history of neighboring bridges. After determining the minimum depth at which the pier would be safe from undermining, the base is located in material with the proper load-carrying capacity as determined by the nature of the material, the past experiences, and the laboratory tests. Consolidation tests indicate the permissible additional load for the allowable amount of settlement. The depth of the pier is usually determined by the anticipated depth of scour and not by the load-carrying capacity of the material.

Construction Methods

Having established the depth of the pier and the allowable unit base pressure, the next step is to decide on the type and method of construction of the pier.

Bridges in Louisiana.—The first two highway bridges constructed on deep foundations in Louisiana by the Department of Highways were across Chef Menteur Pass and The Rigolets, the contracts for which were signed on July

19, 1927. Double-wall, cylindrical-steel caissons of the floating type were used on these two bridges, as well as on the bridges at Morgan City and Krotz Springs across the Atchafalaya River in Louisiana, the contracts for which were signed on September 30, 1931.

A double-wall, cylindrical-steel caisson to be sunk by open dredging consists of an outer and inner cylindrical-steel shell, the diameter of the inner shell being several feet less than the diameter of the outer shell. The inner and outer shells are braced together with horizontal frames, usually composed of angles, and are joined at the bottom with a conical plate to form a cutting edge that is heavily reinforced at the bottom edge where the conical plate joins the outside shell. The caisson material is usually shipped in sections and assembled at the bridge site. The caisson may be assembled on ways and launched like a ship, or it may be assembled on a barge—temporarily supported from a working dock by screws, or hoists, while the barge is flooded and floated out from under the caisson—after which the caisson is lowered into the water. After the caisson has been floated, it is towed into position and encircled by a ring of timber piles that hold the caisson in position. On occasion sheet-steel piling is driven inside the timber-pile ring to provide "quiet water" in order to permit easier handling and location of the caisson.

Caisson Design.—Concrete is deposited in the space between the inner and outer shells, after the caisson has been located, to cause the caisson to settle on the bottom of the stream. The shell is made of sufficient height to keep the top of the caisson above water. Additional sections of steel shell are added and more concrete is deposited; this process is continued until the concrete is brought above the water level, after which the shell is discontinued and the concrete above this height is deposited in removable forms. During this process material is excavated, with a clamshell bucket, in the dredging well (the area inside the inner steel shell) as is necessary to keep the caisson plumb and on line. After the concrete has been brought above the water level, the process of alternately pouring concrete and dredging and sinking is continued until the cutting edge reaches the required depth. If the material found at the proposed depth is unsatisfactory, the sinking is continued until the cutting edge is in satisfactory material, at which time the dredging well and cutting edge are cleaned out, and the concrete for the seal course is deposited under water.

Quite often the dredging well is unwatered to permit inspection of the pier and the seal course and to check more accurately the position of the cutting edge. Additional concrete is then poured into the well and the well is flooded.

The diameter of the caissons is influenced by several factors. The dimensions at the top of the pier are determined by the requirements of the superstructure, and these dimensions determine the minimum size of the caisson. The area of the base must be large enough so that the additional unit pressure under the base will not exceed the safe supporting capacity of the material upon which it rests. In determining the additional base pressure, it is customary to neglect the effect of skin friction, as it is not known how much of the material may be lost through scouring. Circular caissons are best adapted for bridges with relatively narrow roadways as in this case the minimum diameter required is not too large. For bridges with very wide roadways,

where two caissons for each pier might be satisfactory, circular caissons may be utilized. Circular-steel shells are easily fabricated and assembled. The greatest advantage in the use of circular caissons is the ease of depositing the concrete for the seal course, since the tremie does not have to be moved from dredging well to dredging well as in the case of rectangular cellular open caissons. There is a division of opinion as to the relative difficulty of controlling circular and rectangular caissons during sinking operations.

The height of steel shell required is dependent on the depth of the water and the nature of the material to be penetrated. The caisson and concrete must be supported principally by skin friction, and the required height of the shell is determined by estimating the penetration which will be required to develop enough skin friction to support the caisson and the amount of concrete necessary to bring the top of the concrete above the water level. The height of the steel shell must be equal to the depth of the water, the penetration, and a sufficient freeboard height above the water level to provide for any expected rise of the water level. If the material in the river bottom is firm, the amount of shell required will not be much more than the depth of the water, but if the material is soft, the amount of shell required may be much greater. In addition, when the river bottom is soft and the water is deep, care must be taken that enough penetration is obtained before the concrete is brought up to a height at which the caisson will be unstable, thus reducing the danger of tipping.

Construction Projects

At Chef Menteur Pass the bottom was of reasonably good material and the greatest amount of shell, 78 ft, was used at Pier 2 where the water was 54 ft deep at the beginning of construction. However, 110.5 ft of shell was required for Pier 3 on the bridge at Morgan City where the water was 53 ft deep at the beginning of construction.

The distance between the inner and outer shell of the caisson determines the weight of the caisson. Except for structural reasons, this dimension is varied in accordance with the type of material to be penetrated. If the material is soft it is desirable to keep the caisson light, whereas a heavier caisson is desirable in firm material to aid in overcoming skin friction during sinking. From the designer's viewpoint, the lighter pier is always desirable for economy of materials as well as for lighter loads on the soil. It is not economical to make the caisson excessively heavy to overcome any possible sinking condition which may occur. Additional effective weight for sinking can be obtained by removing water from the dredging well, thus reducing the effect of buoyancy. The caisson may also be temporarily loaded with pig iron, or compartments may be provided for loading with sand or water.

Fixed Jets.—To assist in the sinking operation, twenty-four fixed jets were built into the caissons for the bridges across Chef Menteur Pass and The Rigolets. These jets were located in quadrants in a circle immediately inside the extreme bottom of the cutting edge. Each quadrant had six jets and an independent feed pipe so that, if the pier should begin to lean, the jets on the high side could be used to aid in righting the pier. The object of these jets was to wash material from under the cutting edge into the dredging well.

In addition to these jets twenty-four additional fixed jets (also in four quadrants of six jets each, and each quadrant having an independent feed pipe) were provided on the caissons for the bridges across the Atchafalaya River at Morgan City and Krotz Springs. The outside jets were installed around the outer wall of the caissons, about 8 ft above the cutting edges, and were directed upward at a slope of about 3 horizontal on 12 vertical. The object of the outside jets was to reduce the friction between the ciassons and the material being penetrated.

Fixed jets have a tendency to clog. On the four bridges mentioned previously it was noted that as the water pump connection was removed from the feed pipe, considerable back pressure developed, resulting in a reverse flow through the jets, which helped to wash in material that eventually clogged the jets. Once the jets were clogged, it was impossible to clear more than one jet in each quadrant. In subsequent designs, the use of fixed jets was abandoned and jetting wells 8 in. in diameter were cast in the walls of the caisson, half of these wells terminating just inside the extreme bottom of the cutting edge and the other half terminating higher up on the sloping face of the cutting edge. Movable jets operated in these jetting wells and along the outside of the ciasson and were found to be more satisfactory than the fixed jets. These jetting wells provided an excellent means of making holes in hard material. Small charges of explosives placed in these holes aided in the sinking operation by shattering the hard material and forcing it into the dredging wells.

Great care should be taken to keep the caisson in a vertical position. When the caisson begins to lean, it may be difficult to correct this condition. Remedial measures include dredging on the outside of the high side of the caisson, loosening the ground on the outside by small charges of explosives, jetting on the inside and the outside of the high side, and rigging of lines to aid in pulling the pier over. In pneumatic caissons, blocks may be inserted under the cutting edge on the low side so as to increase the resistance to sinking on that side. If the cutting edge is out of position, the only way that the condition can be remedied is by leaning the pier and continuing the sinking. The type of construction used above the caisson may be any type that is preferred, but the dredging wells must be kept open until the sinking operation is completed.

Pier Sinking.—The contracts for the bridges at Morgan City and Krotz Springs provided that the initial sinking of the caissons be accomplished by the pneumatic process because it was feared that obstructions, such as submerged logs, might be encountered in the earlier stages of sinking. These obstructions could be more easily removed if the caisson were sunk by the pneumatic method than by any other method. It was further provided that the sinking under compressed air could be continued until the foundation material appeared free of obstructions or the limits of air pressure were reached. However, at Morgan City, because of the soft composition of the river bottom, it was thought best to sink the caissons some distance into this soft material before applying compressed air. Consequently, the caisson was designed with a removable circular steel diaphragm to form the roof of the working chamber. This roof could be lowered into the dredging well and bolted to a shelf by divers. The roof could be removed by the divers when the limits of pneumatic excava-

tion were reached so that the sinking could be continued by open dredging. The construction of the caissons for the bridge at Krotz Springs was identical.

With 50 ft of concrete in the caisson of Pier 3 at Morgan City, the cutting edge reached a depth of 87.5 ft before the material in the dredging well could be removed to below the shelf provided for the roof of the working chamber (so that the roof could be installed and air applied). Sinking by the pneumatic process proceeded for 21 ft until the cutting edge was 109 ft below low water, at which time the roof was removed and sinking was continued by open dredging. The maximum pressure used was 46 lb per sq in. When completed, the cutting edge of the pier was 176.5 ft below low water, and was the world's deepest pier at the time of completion.

The caisson data for the four bridges previously mentioned are listed in Table 1.

TABLE 1.—CAISSON DATA FOR HIGHWAY BRIDGES IN LOUISIANA

Bridge location	Piers	Caisson diameter, in feet	Dredging-well depth, in feet	Depth below low water, in feet
Chef Menteur Pass	5	28	14	82 to 126.5
The Rigolets	5	28	14	92
Morgan City	4	44	20	112.9 to 176.5
Krotz Springs	4	44	20	140 to 150

Wax Lake Outlet.—The construction of the Wax Lake Outlet in St. Mary Parish, Louisiana, provided an additional outlet for the escape of the floodwaters from Six Mile Lake in the Lower Atchafalaya River Basin to the Gulf of Mexico, necessitated the construction of a new highway bridge on U. S. Highway 90 (the Old Spanish Trail) near Calumet, La., the contract for which was signed on November 28, 1939. The Wax Lake Outlet was to be constructed with a bottom width of 300 ft at El. −45 (referred to Mean Gulf Level (MGL) at the bridge site).

Two deep channel piers were required by the adopted layout, as it was believed the channel might eventually scour under the action of floodwaters to approximately El. −90 MGL. The borings indicated that these piers should be at El. −149 MGL to be safe from scouring and for the required stability, and the piers were constructed to within a foot of this depth.

The contact for the construction of this bridge included the excavation of the channel at the bridge site, which was not to be done until after the piers were completed. This rather unusual condition enabled the main channel piers to be constructed on dry land.

Open cylindrical concrete caissons, 38 ft in diameter and 40 ft high, with one dredging well 22 ft in diameter, and steel cutting edges 12 ft high were used. All the concrete, except that in the cutting edges, was poured in removable forms which permitted examination of all the concrete before sinking. There are many advantages in being able to construct piers in this manner. The caissons can be constructed in exact position, and the difficulty of locating floating caissons in moving water is eliminated.

The design drawings provided for twenty-four 8-in.-diameter vertical jetting wells to be cast in the walls of the pier, twelve terminating near the cutting edge, and twelve terminating higher up on the sloping face of the cutting

edge. In addition, the contractor decided to provide eighteen fixed horizontal jets on the outside of the caisson about 10 ft above the cutting edge, arranged in six segments of three jets, each segment having an independent feed pipe.

The determination of the height of the caisson for piers of this type is a matter of engineering judgment and experience. The caisson should be high enough to provide stability during construction and high enough to furnish a reasonable amount of weight to aid in the sinking operation. No particular difficulty was encountered in the sinking of the Wax Lake Outlet caissons. Concrete caissons 30 ft high have been used in a number of instances. Some engineers are of the opinion that caissons less than 30 ft high should be used with caution for deep-pier construction.

After the caissons had reached the proposed depth, it was found to be impossible to excavate closer than 7 ft from the cutting edges, and seal courses of tremie concrete 27 ft deep were poured under water. After this seal concrete hardened, the dredging wells were unwatered, the concrete was inspected, the laitance was removed from the top of the seal course, about 6 ft of concrete were deposited in the dry above the wet seal, and the dredging well was again filled with water.

Sand-Island Method

There are few opportunities to construct deep piers on dry land, but the "sand-island method" offers many of the same advantages. This method consists of erecting a large steel shell, penetrating some distance into the river bottom, and extending above the expected water level, which is then filled with sand. Concrete caissons can then be constructed on these sand islands completely above the water level. After completion of the pier, the shell is salvaged. Sand islands are vulnerable to erosion, however, as undermining of the steel shell will permit the fill material to escape. It is advisable to protect the bottom by mattresses.

On June 15, 1937, the contract was signed for the four channel piers for the Mississippi River bridge at Baton Rouge, La., and these piers were constructed by the sand-island method and were sunk by open dredging. Two of the sand islands were constructed with circular steel shells, and two were constructed with sheet-steel piling; the steel shells being used for Piers 3 and 4 were located in the deepest water. The depth of the water was 69 ft at Pier 3 and 40 ft at Pier 4 (below MGL).

Mattresses measuring 250 ft by 450 ft were constructed at the site of Piers 3 and 4, after which the timber piles for the construction docks were driven. Timber piles 108 ft long were driven at Pier 4, and piles 135 ft long were driven at Pier 3. The assembly of the shells, which were 111 ft in diameter at Pier 4 and 121 ft in diameter at Pier 3, was then begun. Several sections of shells, supported on the dock piles, were assembled. These sections were then lowered to a new connection with the dock piles by use of a number of hoist frames. Each frame was equipped with a hand hoist, located on the construction docks around the circumference of the shells, and the process was continued until the shells had penetrated 10 ft into the river bottom through the mattresses and extended 30 ft above low water. The shells were filled 15 ft

above the water level with material obtained 2000 ft from the bridge. The fill material was loaded into barges by means of an hydraulic dredge, and the material was placed in the sand islands with clamshell buckets after the barges were towed to the pier site.

The depth of the water at Piers 2 and 5 was very much less than that at Piers 3 and 4, and the sand islands for these piers were constructed with sheet-steel piling. Rectangular, cellular concrete open caissons were constructed on the sand islands and were sunk to the required depths by open dredging, the deepest being Pier 2 which extended 183 ft below low water.

The sand-island method was used in the construction of three other bridges by the Department of Highways, State of Louisiana. On two of these bridges pneumatic concrete caissons were used, one across the Red River at Moncla, La. (the contract for which was signed in December, 1946) and one across the Red River near Miller's Bluff, La. (the contract for which was signed in March, 1951). Open concrete caissons were used on the third bridge across the Calcasieu River at Lake Charles, La., the contract for which was signed in February, 1948.

The Bridge at Lake Charles.—The bridge at Lake Charles has two 26-ft roadways, separated by a 4-ft median and two 3-ft sidewalks. One navigation channel, 200 ft wide, is provided with 135-ft vertical clearance. The two channel piers, Piers 4 and 5, were each constructed with two open cylindrical concrete caissons, 67.5 ft on centers.

The caissons for Piers 4 and 5 were originally designed as open double-wall steel cylindrical caissons, 36 ft high and 32 ft in diameter with 18-ft-diameter dredging wells. Concrete cylinders 31 ft in diameter with 18-ft dredging wells were provided above the caissons. These cylinders were 86 ft high at Pier 4 and 74 ft high at Pier 5, and were capped with 9 ft of concrete on which the pier shafts were constructed. An attempt was made to reduce the skin friction during sinking by decreasing the diameter of the pier from 32 ft to 31 ft at the top of the 36-ft-high caisson. The value of this offset is problematical in sand or in plastic soil, as the material probably flows in against the smaller diameter section.

After bids were received, in accordance with supplemental agreements with the conctractor, the caissons were redesigned to eliminate the steel shells and to use concrete caissons of the same dimensions. Steel sheet pile sand islands were constructed, separate sand islands being used for each caisson. The depth of the water at low stage was 20 ft at each pier, and extreme high water was only 8 ft above low stage. The river bottom was firm and not subject to much scouring, all of which was very favorable to the sand-island method and the redesign of the piers resulted in a saving of approximately $50,000.00.

The caissons for Pier 4 extended 135 ft below low water, and those for Pier 5 were 122 ft deep. The material penetrated was predominately hard clay and sand, and it was necessary to load the caissons to aid in the sinking operation. Cast iron pigs were used as weights. It would not have been economical to make the caisson heavy enough to avoid the use of temporary loading.

The Bridge at Moncla.—The bridge across the Red River at Moncla consists of one 360-ft vertical-lift span, flanked on each side by one 360-ft fixed

high-level truss, requiring two channel piers and two bank piers, as the river was less than 1,000 ft wide at the selected bridging point. All four piers were constructed to the same depth, about 70 ft below extreme low water, as the banks of the Red River are generally subject to excessive caving. Some caving of the banks upstream from the bridge has occurred, and it is very likely that extensive bank protection works are necessary.

Pneumatic concrete caissons were used for all four piers, with the two channel piers being designed for use of the sand-island method. The caissons were very similar to those used at Miller's Bluff, described subsequently, the principal difference being that the caissons at Moncla had lenticular ends to lessen the scouring action of the water as much as possible, whereas those at Miller's Bluff had cylindrical ends. The cylindrical ends were used in an attempt to reduce the cost of the forms, as it was felt that the hydraulic qualities of the cylindrical ends were not greatly inferior to the lenticular ends.

The pneumatic process was selected for the construction of these piers because the borings indicated that the material might be too hard for open dredging. However, the contractor requested permission, which was granted, to start sinking the caissons by open dredging and to continue the open method until the nature of the material made it necessary to use the pneumatic method.

The Bridge at Miller's Bluff.—The bridge across the Red River at Miller's Bluff is a fixed high-level bridge providing 50-ft clearance above extreme high water (which is about 40 ft above low water) consisting of five 360-ft, high-level trusses flanked by I-beam spans. Although this crossing is approximately 250 miles upstream from Moncla, the Red River is wider at Miller's Bluff. This is because of the hard bluffs which form the east bank just upstream from the bridge location. These bluffs deflect the water against the west bank, causing caving. At the time the bridge survey was made (September, 1949) the west bank had been stable since 1938, which was the date of the earliest available accurate records. By July, 1950, 250 ft of the west bank had caved in, and the bridge layout was made on that basis. Pier 1 was set back approximately 450 ft from the west bank just inside the existing levee, and all six piers for the the five 360-ft trusses were designed as deep piers, extending about 65 ft below low water. The river bottom is composed of highly erodible materials, but the borings indicated that piers of this depth would be safe from undermining by scouring action. Bids were received for the construction of the substructure in January, 1951. By March, 1951, when the contract was signed, 250 ft more of the west bank had caved in. This was not unexpected, as the bridge had been planned so that 600 ft of caving would not endanger the structure. In the meantime, investigations were begun to determine what type of bank protection could be constructed to stop further loss of the bank, as it appeared to be more economical to force the river to remain under the bridge, than to extend the bridge over the river if the river were permitted to continue its westward movement.

Bids were received on August 8, 1951, for a system of trail and spur dikes extending about ½ mile upstream from the bridge. Dikes of this type have been constructed in numerous locations along the Red River by the Corps of Engineers, United States Department of the Army, and have proved to be

very effective in preventing bank erosion. A contract for approximately $210,000.00 for bank protection works was signed on August 27, 1951. By September, 1951, an additional 300 ft of the west bank had caved in, which is about the limit for the bridge layout, and in the two years between September, 1949, and September, 1951, approximately 800 ft of bank, which had been stable for the previous 11 years, were lost.

All six piers are identical except for height, and consist of a concrete caisson 30 ft high and rectangular in shape with cylindrical ends, the extreme outside dimensions being 26 ft by 50 ft in plan; a lower shaft, also rectangular with cylindrical ends in plan, 60 ft high and extending above high water; and an upper shaft similar to the lower shaft except smaller in size, and differing in height for the various piers.

For maximum economy, the shafts were not tapered, and, except for the forms for the copings of the lower and upper shafts, only three outside forms were used by the contractor—one for the caissons (used 18 times), one for the lower shafts (used 36 times), and one for the upper shafts (used 18 times).

Sheet-steel pile sand islands were used for three of the piers, and the other three were constructed as dry-land piers. The caissons were sunk by a combination of open dredging and pneumatic excavation. Because the very hard material which makes pneumatic excavation necessary lies at some distance below the surface, the initial sinking of the caissons was accomplished by open dredging, and the pneumatic method was used when the material became too hard for open dredging. Two pay items were provided for excavation, one for open excavation, for which the contractor bid $3.70 per cu yd, and one for pneumatic excavation, for which the contractor bid $22.00 per cu yd.

Three dredging wells, each 8 ft in diameter were provided in the caissons and lower shafts. Recesses were provided in these dredging wells, and when the open dredging was discontinued, concrete plugs 7 ft thick were poured into the wells above the water level and the man and material shafts fastened to flanges in the concrete plugs. The water was then forced out by compressed air, and the men descended into the working chamber, and the sinking was continued. When the caisson was founded, the working chamber and wells in the caisson were filled with concrete, in the dry, under air pressure. The wells in the lower shaft were not filled.

The crossing at Miller's Bluff was the best location which could be found for this bridge, and it is rather typical of the Red River. Trouble has been experienced at practically all existing bridge locations, and bank protection works are vital.

Conclusions

It is desirable, in the preparation of plans and specifications, to permit the contractor considerable latitude in the method to be used in constructing piers. The most economical method may be determined by the type of equipment available to the contractors who are in a position to bid on the work. However, design of the piers is within the province of the engineer who should study both the construction methods and the construction costs.